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# Using global positioning system for orthometric height determination for gravity surveys in Ladakh Himalaya

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**Though GPS can be used for precise 3-D positioning, the height thus measured is spheroidal which needs to be converted to the orthometric height for any practical use. This requires knowledge of the geoid undulation that can either be measured using GPS/levelling technique, or can be modelled from gravity data. We carried out extensive field measurements along a 100 km long transect in Ladakh Himalaya to study the viability of using the GPS for orthometric height determinations required for gravity surveys. Geoid of the study area was also predicted using global gravity models, e.g. OSU91 and EGM96. It is seen that even on high and difficult terrain like that of the Himalaya, GPS can be used for orthometric height determination with an absolute accuracy of 1–2 m.**

ACCURATE three-dimensional relative positioning is now possible using GPS[1–4]. A 100 km long baseline can be measured with a repeatability of only few mm. Exhaustive field experiments were conducted by USGS[2]. The RMS residual about the best fit line of 233 km long baseline were 0.03, 0.05 and 0.18 ppm for the north, east and vertical components. The difference between GPS results and Geodilite (a high precision LASER distance measurement) was always less than 1 s.d. A GPS data comparison between VLBI and GPS measurements over common baseline gave a difference of 0.05 ppm, close to 1 s.d. of GPS data.

The initial accuracy barrier like ‘anti-spoofing’ and ‘selective availability’ (S/A) imposed by the American defence has been cleverly bypassed by the scientists. Several tactical developments have pushed the accuracy level increasingly higher. Use of carrier wave in post-processing for increasing measurement resolution, dual frequency receiver to reduce ionospheric delays, differential mode to avoid S/A, use of precise ephemeries for better accuracy and use of better tropospheric models are few to name. This low cost, highly accurate and easy to use space geodetic technique is distinctly advantageous over the conventional terrestrial geodetic techniques like triangulation, trilateration and levelling. Unlike terrestrial surveys, GPS does not need line-of-sight clearance, measurement length is not limited by optical visibility and is much faster in operation.

GPS uses an earth-fixed earth-centred Cartesian coordinate system called World Geodetic System-84 (WGS-84), and gives coordinates of the measurement point in terms of $X$, $Y$ and $Z$. Whereas these components can readily be converted in terms of latitude and longitude in any other system, height is given above a reference spheroid which has very little practical use. Conversion of this spheroidal height into orthometric (mean sea level) height, i.e. the height over geoid, requires knowledge about the geoid-spheroid separation, known as geoid undulation or geoid height at the measurement point. Geoid height of a single point on the surface can be actually measured by combined GPS and levelling measurements over the common point, or geoid undulation of a region can be modelled from gravity data. To test the viability of using GPS for height measurements, we carried out levelling and GPS surveys along a 100 km long profile in Ladakh of western Himalaya. The same geoid undulation was also computed from the global gravity model.

Spheroid is a mathematical, smooth surface, closest to the actual surface of the earth. Geoid is an equipotential gravity surface, a very close approximation to the mean sea level (msl), and is generally undulating depending on the local sub-surface mass distribution. As sea surface coincides with the geoid, it is much easier to map geoid undulations over the oceanic region. In fact, the geoid over the entire oceanic surface of the earth has been mapped with high degree of resolution using satellite altimetry. Before the invention of the GPS, geoid undulation measurements over the continental parts were extremely difficult, as it required astronomical measurements, which were not very accurate either. Consequently, in difficult and adverse terrains like the Himalaya, geoid undulations are known with very poor resolution.

While conventional levelling surveys provide heights ($H$) over geoid, and GPS provides height over some spheroid ($h$), common measurement of levelling and GPS on a surface point gives the geoid undulation ($N$) of that point (Figure 1), defined by

$$N = h - H + \varepsilon, \qquad (1)$$

where $\varepsilon$ is small quantity due to the deflection of the vertical[5], which can be avoided if instead of absolute geoid undulation, we consider variation of geoid undulation ($\Delta N$) between two points A and B,

$$\Delta N = \Delta h - \Delta H, \qquad (2)$$

assuming the distance between two points is small, so that the variation of the deflection of the vertical can be neglected[6,7]. This is true within 20 km length which is the range of the GPS fast-static survey.

As geoid undulation is usually smooth, by limited use of GPS-levelling survey, geoid undulation in a region can be measured over a few points to construct a reasonably accurate geoid undulation surface of the area[8-11]. Once geoid undulation model of the survey area is known, GPS can be used extensively to determine orthometric heights of any point within this area. In the difficult terrain like the Himalaya where measurements can only be made along a profile, e.g. road, simple linear interpolation of few measured geoid points should be sufficient to provide reasonable accuracy for the intermediate points. The number of actual measurement points in a region depends upon the accuracy requirement for interpolated points, a tectonic set-up, and topography of the region.

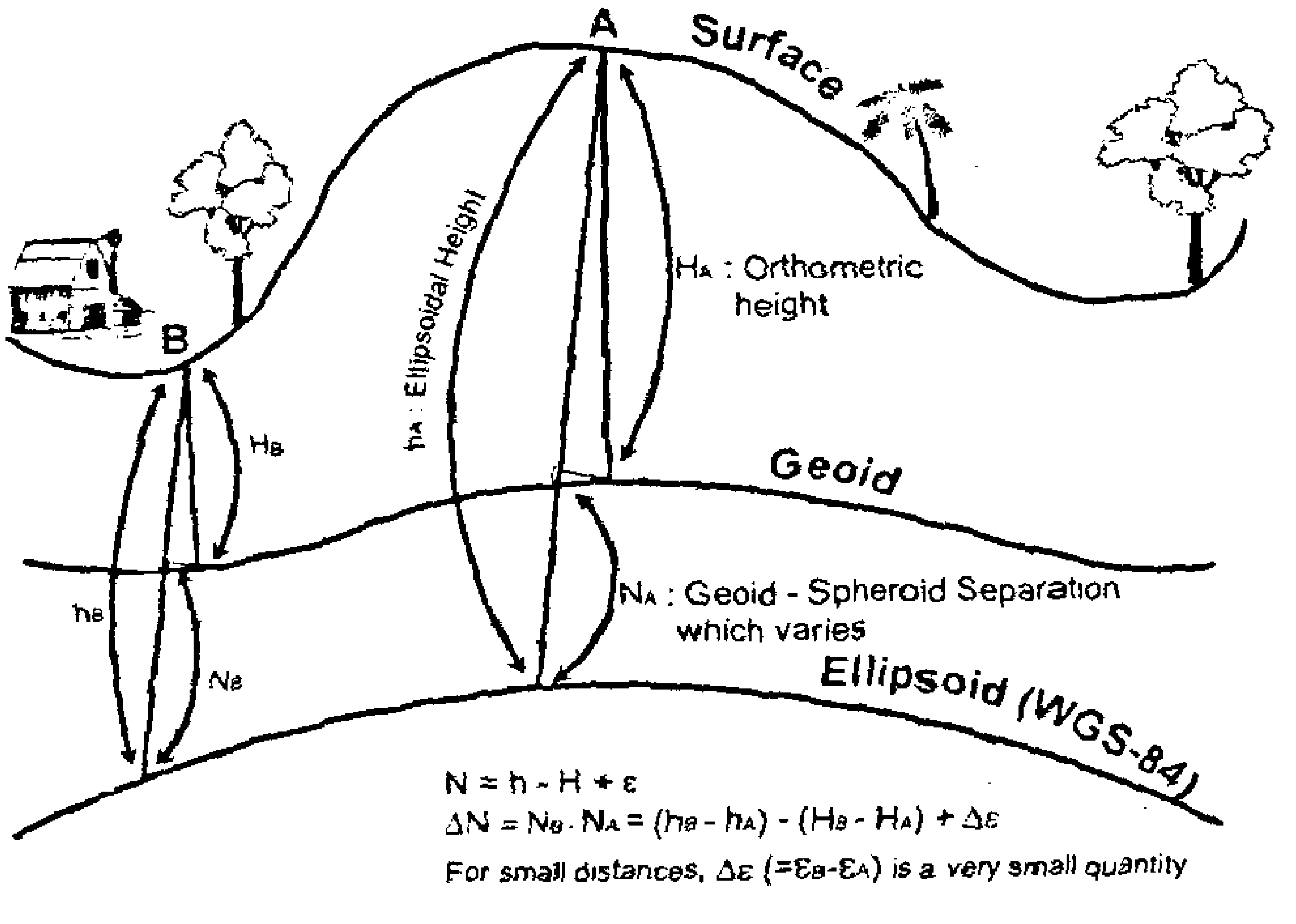

**Figure 1.** Orthometric height ($H$) is measured over the geoid, whereas GPS gives height ($h$) over WGS84 spheroid. Variation of the deviation of the vertical from normal $\varepsilon$ is small over small distance.

Geoid can also be modelled using gravity data[12-14]. However, it requires dense coverage of surface gravity data. Unfortunately, almost complete lack of surface gravity data over the Himalaya, particularly the higher Himalayan regions does not allow computation of the geoid undulation model with high accuracy and resolution.

We selected the nearly 100 km long Rumtse–Leh–Khardungla profile in Ladakh of north-western Himalaya. The road section is marked by steeply undulating terrain with elevation varying between 3000 and 5400 m, and reaches the highest motorable road in the world, Khardungla. Three Survey of India (SOI) GTS levelling benchmarks at Rumtse, Upshi, Igu and Leh were used for tying up our levelling network. We established a total of 20 benchmarks over which levelling measurements were carried out using Sokia Set 2C Total Station (a micro-processor based EDM–theodolite combination) instrument. Levelling measurements were carried out in 1994, 1995 and 1996. As no SOI levelling line exists to the north of Leh along this transect, we repeated Leh–Khardungla section of our levelling measurements twice, and closed the loop between every two consecutive gravity/GPS stations at 1–2 km interval. The loop closure errors were of the order of 2–5 cm.

GPS measurements were carried out using two dual frequency Trimble 4000 SSE receivers in 'fast static' mode. The basic principle of this technique is to keep one receiver fixed and continuously running at the 'base station', while the other receiver is used as a mobile unit to occupy a series of individual measurement points, one after another, within 20 km range of the base station. No on-line communication is needed between the base and the roving unit. Each station takes 8–20 minutes occupation time depending on the number of available satallites.

We established three base stations at Upshi, Igu and Leh. Leh (SABU) station was operated continuously for five days for tying it up with other IGS permanent stations. Later, both Upshi and Igu base stations were tied with Leh station by 5 h of common occupation. Sixty-two GPS fast-static stations were established along this section, out of which 20 were on the pre-established levelling benchmarks. All these stations were used for gravity field measurements. GPS measurements were carried out in 1995 and 1996, and some stations were repeated twice in Leh–Khardungla section.

GPS data were processed using Bernese 4.0 post processing software. To compute the accurate position of Leh (SABU) base station in ITRF94 (International Terrestrial Reference Frame), we used five days common data of Lhasa and Kitab IGS stations, which are around 1500–2000 km away. The accurate coordinates in ITRF94 for these stations were obtained from IGS website. Most of the ambiguities were resolved using quasi-inosphere free (QIF) strategy[15]. RMS of single difference observations used for parameter estimations, for all the days were between 0.0023 and 0.0025. Unweighted RMS values with respect to the 5 days combined solution are 3.1, 10.8 and 8.2 mm for north, east and vertical components respectively. Upshi and Igu base stations were similarly fixed relative to Leh. The fast-static data were then processed using SEARCH ambiguity resolution strategy[15] relative to the respective base stations. IGS precise satellite ephemerides were used for the entire processing. RMS errors of the station coordinates were of the order of 0.001 arcsec for latitude and longitude, and of the order of 1 cm for the height. The repeatability cannot be assessed as fast-static stations were occupied only once, except for the Leh–Khardungla section where repeatability is 1–5 cm.

The levelling data were processed using a Fortran program written by the first author. The refraction errors are computed for each EDM-target setting. A statistical average of the readings of each setting is taken, after eliminating outliers. Back and forth loop closure error is distributed linearly within all intermediate stations. After relative heights are determined for the entire network, heights are converted into absolute orthometric heights using the SOI supplied levelling heights for the benchmarks. Though the measurement accuracy of both SOI benchmarks and our benchmarks are high, SOI supplied elevation values were masked after the first decimal place. Difference between orthometric heights and GPS derived heights give geoid heights for each of the 20 points (Figure 2). The scatter of the profile points about a smooth geoid is up to few tens of cm, and this is likely to be the approximate true error of the combined GPS and levelling measurements.

Geoid undulation was also computed using the latest global gravity models, i.e. OSU91 and EGM96[16]. Spherical harmonic coefficients of these models are available at NIMA website. A slightly modified version of a FORTRAN program developed by Rapp[17] was used to compute geoidal undulations at the measurement points.

It is seen (Figure 2) that OSU91 derived geoid model matches closely with the measured geoid whereas EGM96 geoid is d.c. shifted by nearly 1 m down relative to both the measured and the OSU91 geoid. The mean difference between the measured geoid undulation and OSU91 and EGM96 derived geoid models are 0.84 and 1.58 m and the s.d.s are 1.08 and 0.46 respectively. The mismatch is more on the northern end of the profile where the topography has steep gradient. The EGM96 model was evaluated using GPS/levelling tests in USA over more than 1000 points and a mean difference of –1.12 m was obtained between the measured and computed geoid undulations[16]. The mean difference is the net effect of vertical datum offsets with the orthometric heights, non-geocentricity in the ellipsoidal heights, as

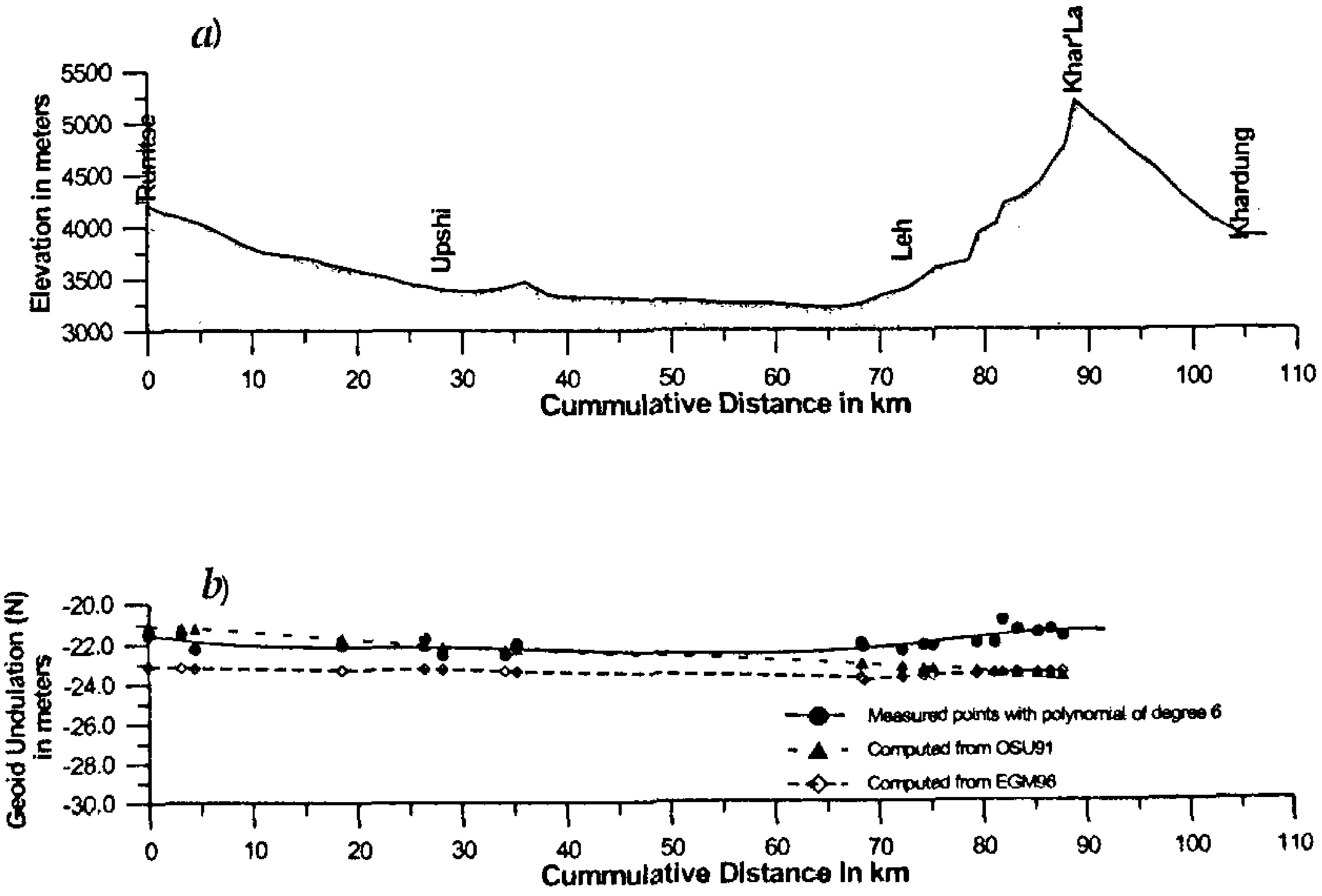

**Figure 2.** *a*, Elevation along the Rumtse–Leh–Khardungla section. Khardungla at 5400 m height is the highest motorable road in the world. *b*, Measured *vis-à-vis* OSU91 and EGM96 derived geoids along the Rumtse–Khardungla section. The northern part with steep topographic gradient has higher deviation between the measured and the computed. Except for the 1.5 m d.c. shift, the EGM96 geoid is better matched with the measured one.

well as errors in the geopotential model. All these effects are expected to be larger over the Himalayas, which are the most tectonically disturbed and elevated part of the earth's surface where very little surface gravity data exists. The first two factors are mainly responsible for the mean difference, lack of sufficient surface gravity data in Ladakh region is mainly responsible for the absence of higher frequency components in the computed geoid. No more than 3–4 gravity stations were existing in the region prior to the present work which established more than 500 gravity stations in the region. A modified spherical harmonic coefficient incorporating new data will be able to predict geoid more closely.

Though mathematically predicted geoid model can be used for orthometric height determination, inclusion of a couple of levelling/GPS station into the network will increase the accuracy of the geoid model by reducing the d.c. shift as mentioned earlier, and will ensure better reliability of the data. If the EGM96 geoid is shifted upward by, say 1.5 m, geoid within the measured line can be predicted with better accuracy to within 0.5 m. In the present form, it is seen that existing gravity model derived geoid models can be used even in the most undulating parts of the Himalaya to reduce GPS measured heights to orthometric heights to within 1–2 m accuracy. 1 m error in height translates to 0.2–0.3 mgal error in Bouguer gravity anomaly. Considering the fact that better overall accuracy in Bouguer gravity anomaly cannot be achieved in higher Himalayan region due to large amount of terrain correction[18] involved, 1–2 m error in height measurement is acceptable. In the plain land, geoid can be better predicted from the gravity data as surface gravity coverage is much denser. Also, over the plain terrain, lesser number of GPS/levelling measurements can be interpolated with better accuracy as undulations of the geoid surface is much smoother compared to the hilly terrain.

From our experience of working with GPS receivers in fast-static mode, we conclude that (1) at least 20 min of GPS data for each measurement point, (2) use of scientific software like Bernese, etc. for post-processing of the data, and (3) inclusion of few levelling/GPS measurements (though not essential) into the GPS fast-static network, can determine orthometric heights with desired level of accuracy. The accuracy of the determined orthometric heights is constrained by the accuracy of the derived geoid model, rather than by that of the GPS measurements.

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